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Measurement of Surface Shear Stress Vectors Using Liquid Crystal Coatings

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Under normal white light illumination and oblique observation, liquid crystal coating (LCC) color-change response to shear depends on both shear stress magnitude as well as the direction of the applied shear relative to the observer's line of sight. These color-change responses were quantified by subjecting a LCC to a wall-jet shear flow and measuring scattered-light spectra using a fiber optic probe and spectrophotometer. At any fixed shear stress magnitude, the maximum color change was measured when the shear vector was aligned with and directed away from the observer; changes in the relative in-plane view angle to either side of this vector/observer aligned position resulted in symmetric Gaussian reductions in measured color change. Based on these results, a surface shear stress vector measurement methodology, involving multiple oblique-view observations of the test surface, was formulated. Under present test conditions, the measurement resolution of this technique was found to be ±1 deg for vector orientations and ±5% for vector magnitudes. An approach to extend the present methodology to full-surface applications is proposed.

Nomenclature

C_f = skin friction coefficient
D = jet exit diameter
I = spectral scattering intensity
N = number of data points used in curve fits or in data-reduction technique
V = velocity
W = white light
X, Y = chromaticity coordinates
α = above-plane view angle, measured positive upward from zero in plane of test surface
β = relative circumferential-view angle in plane of test surface measured between observer line of sight and shear vector (positive clockwise)
ΔP = pressure difference used to drive jet flow
λ = wavelength of light
λ_D = dominant wavelength
ρ = density
τ = magnitude of surface shear stress vector
ϕ = circumferential angle in plane of test surface, measured positive counterclockwise from origin
ϕ_τ = orientation of surface shear stress vector, directed away from observer with line-of-sight at $\phi = \phi_\tau$

Subscripts

C = camera
J = jet
L = light
P = probe
r = reference value

Introduction

THE objective of the present research is to develop a technique for the areal measurement of the surface shear stress distribution acting on any test surface immersed in a three-dimensional flowfield. In fundamental experiments, full-surface measurements of both the magnitudes and the directions of such skin-friction forces would provide modelers with detailed data sets for code-validation purposes, ultimately leading to more advanced design tools. Once proven, the application of such a measurement capability to the prototype testing of advanced aerodynamic configurations could greatly increase the productivity of ground-based facilities.

A review of the state of the art[1-3] shows that numerous point-measurement techniques are currently available to determine surface shear stress magnitude; several of these methods can also be used to measure local shear stress direction. However, no full-surface, vector-measurement capability presently exists. The method presented here demonstrates that both the magnitude and direction of surface shear stress vectors can be accurately quantified from measurements of the color-change response of liquid crystal coatings subjected to such shearing forces. An approach to extend the present point-measurement method to a full-surface technique is outlined.

Liquid Crystals

Cholesteric liquid crystals reside in a highly anisotropic mesophase that exists between the solid and isotropic-liquid phases of some organic compounds.[4] Such materials can exhibit birefringent optical properties that are characteristic of a crystalline solid state. Once aligned by shear, molecules within a thin liquid crystal coating scatter incident white light as a spectrum of colors, with each color at a different orientation relative to the surface. Shear stress sensitive and temperature insensitive compounds now exist; one such compound, Hallcrest mixture CN/R3, was used in the present research. For such coatings, "color play," i.e., discerned color changes at a fixed angle of observation for a fixed angle of illumination, results solely from the application of shear stress. Such color changes are continuous and reversible, with time response of order milliseconds. Based on these characteristics, liquid crystal coatings have been used to visualize shear stress patterns on aerodynamic surfaces in both laboratory[5-8] and flight-test[9] applications.

Initial attempts at using liquid crystal mixtures available in the late 1960s to measure surface shear stress magnitude were not successful.[10] Recently, however, two major advances in the liquid crystal method were achieved that demonstrated its potential use as a measurement technique. First, under carefully controlled laboratory conditions, quantitative calibrations between observed color changes and changes in surface shear stress magnitude were shown to be possible.[11-15] Second, Reda et al.[16] have shown that,

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